



CO₂ emission reduction by reuse of building material waste in the Japanese cement industry



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ABSTRACT

CO₂ emitted from calcination processes in kilns comprises 60% of all emissions from cement production. The chemical components of building materials, demolished inorganic building materials (DIBMs), and waste concrete powder (WCP) are similar to those of cement minerals. Therefore, if DIBMs are used as a cement substitute material along with limestone, the quantity of disposed waste and the use of limestone will likely be reduced, as will CO₂ emissions during cement production. This study proposes a recycling method for recycled cement, using DIBMs and WCP as cement substitute materials, and the properties of trial recycled cement were evaluated. The mortar specimen using recycled cement showed a high compressive strength, as did the ordinary Portland cement mortar. According to the proposed composition, the producible recycled cement was derived from 0.5% to 9.1% of annual cement production (about 57.6 million tons) in Japan. Additionally, the CO₂ reduction by usage of recycled cement ranged from 0.06 million tons to 0.72 million tons from the total annual CO₂ emissions from cement production (about 29.4 million tons), using natural resources in Japan.

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1. Introduction

1.1. CO₂ emissions in the cement industry

The industrial sector is responsible for 30–70% [1–9] of the total global energy consumption and CO₂ emissions; the countries with the highest CO₂ emissions are shown in Fig. 1 [1]. The cement industry is one of the major contributors to greenhouse gas emissions, specifically that of CO₂, and consumes about 12–15% of total industrial energy usage [3]. Therefore, the cement industry contributes about 7% of the total worldwide CO₂ emissions as a result of fossil fuel burning (about 1.8 Gt of CO₂ emissions annually) [4]. This is due to the calcination of raw materials for the production of cement and the burning of fuels needed to maintain high temperatures in a kiln [5]. The world demand for cement was 2283 million tons (Mt) in 2005, and China accounted for about 47% of the total demand. It is predicted that the demand will increase to about 2836 Mt in the year 2010 [6]. It was also reported that China, India, the United States, and Japan produce the largest quantities of cement, globally (Table 1) [6–8].

Therefore, CO₂ emission reduction in the cement industry is of importance. Focusing on cement materials and energies, some alternative techniques that can reduce CO₂ emissions in cement manufacturing are outlined below [5,9–15]

- use of waste heat as an alternative source of energy;
- use of blended cement by reducing the clinker/cement ratio;
- preparation of the raw mixture with non-carbonated calcium;
- use of alternative raw materials that contain carbonates (e.g., fly ash, blast furnace slag, and inorganic building materials).

1.2. Reducing CO₂ emissions by reusing waste building materials

The existing research is focused mainly on the technical, economic, and environmental effects of the use of industrial solid waste as alternative energies, fuels, and raw materials in the cement industry [9–17]. Among the various CO₂ reduction techniques, this study focuses on the use of alternative raw materials that contain carbonates (waste concrete powder and inorganic building material wastes) as a cement substitute material. HuXing [18] and Puertas [19] confirmed the technical viability of utilizing certain types of sludge and waste building materials as raw materials in the mixes used to manufacture Portland cement clinker.

Considering the fact that the chemical components of demolished inorganic building materials (DIBMs) and waste concrete powder (WCP) are very similar to the chemical composition of cement materials, both types could be used as raw materials in the manufacture of Portland cement clinker. The amount of waste discharged from the construction industry constitutes approximately 20% of all industrial wastes in Japan, and the space allotted

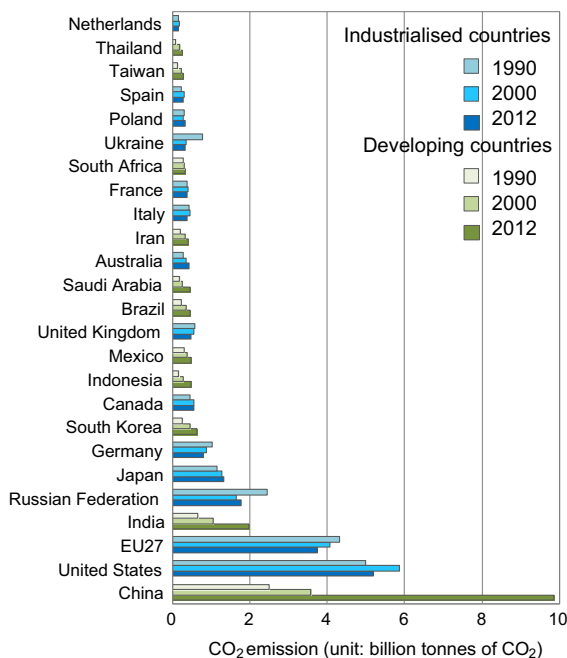


Fig. 1. Largest CO₂-emitting countries [2].

Table 1
Annual global cement production statistics (million tons) [1,6,8].

Country	2003	2005	2007	2009	2011	2012
China	865.2	1079.6	1377.8	1637.1	2100.0	2150.0
India	126.7	146.8	172.9	193.1	240.0	250.0
United states	92.9	99.4	95.5	71.9	68.6	74.0
Japan	73.8	72.7	71.4	59.6	51.3	52.0
Turkey	38.1	45.6	50.8	57.6	63.4	60.0
Iran	30.5	32.6	40.0	56.3	61.0	65.0
South Korea	59.7	49.1	54.4	52.2	48.3	49.0
Brazil	35.3	39.2	47.2	52.3	64.1	70.0
Vietnam	24.1	30.8	35.7	48.0	59.0	65.0
Egypt	32.7	38.9	40.1	46.9	44.0	44.0
Russian Federation	41.4	49.5	59.9	47.2	55.6	60.0
Indonesia	34.9	36.1	39.9	39.7	30.0	31.0
Saudi Arabia	24.1	26.1	30.3	37.8	48.4	43.0
Thailand	35.6	37.9	43.2	37.7	36.7	33.0
Mexico	31.8	36.7	39.9	37.1	35.4	36.0
Italy	43.5	46.4	47.5	36.2	33.1	32.0
Spain	44.8	50.3	54.7	30.6	22.2	20.0
Germany	33.6	31.9	33.4	30.4	33.5	34.0
Pakistan	11.3	15.8	26.3	30.9	32.0	32.0
Other countries (rounded)	–	–	–	–	470.0	500.0
World total (rounded)	–	–	–	–	3600.0	3700.0

for final waste disposal is expected to reach its saturation point within a few years [20]. As a result, the necessity for recycling concrete waste and DIBMs, which account for most of the construction waste, has been increasing with each year. Concrete waste, which constitutes more than 70% of construction waste, is recycled and used as aggregate [20–23]. Recycling of concrete rubble, which account for 30–40% of total construction-related waste, for road bottoming has been promoted in particular as a national policy in Japan. Nevertheless, reductions in the length of new road construction in recent years have undermined the demand for road bottoming, requiring increased efforts to seek technical and social solutions for reducing the amount of disposed concrete rubble. The reduction in the residual capacities of final

disposal areas in Japan, which has become an increasingly serious issue in recent years, also underlines the need for a resource-recycling society [20,23]. While over 90% of recycled aggregates have been used as roadbed material, the demand for roadbed is expected to decrease because the new road building has become increasingly saturated. Therefore the needs to use recycled aggregates and WCP in concrete production have increased exponentially [23]. However, it is necessary to examine past studies of technologies involved with re-usage of WCP, which is generated from the production of recycled aggregates and is expected to increase rapidly in quantity as shown in Table 2 [23]. In addition, it is difficult to reduce the final disposal quantity of DIBMs (tile, brick, etc.), because current separating dismantlement of building is mostly conducted focusing on concrete, asphalt, wood and metal waste by construction material recycling law [22]. Therefore, it is also necessary to identify the quantity of waste per type of DIBMs and to study the construction of a recycling system as a cement raw material, taking into account the discharge quantity [20,22].

World cement production totaled about 3.4 billion tons in 2011, and this demand has continued to increase in conjunction with economic and urban development, especially in East Asia and particularly in China [24]. In Japan, cement production totaled about 57.6 million tons in 2012 and carbon dioxide (CO₂) generated from cement production constitutes approximately 4% of the total industrial emissions nationwide [25–27]. In particular, the quantity of CO₂ emitted from the calcination process in cement production accounts for nearly 60% of all CO₂ emissions. The chemical components of DIBMs, such as WCP, are similar to those of cement [28–30].

Table 2
Recycled products for 1 t of concrete waste in Japan.

Production method	Recycled products		
	R_{RCA} (t)	R_{RFA} (t)	By-product and WCP (t)
Heated scrubbing	0.35	0.3	0.35
Mechanical scrubbing	0.3	–	0.70
Gravity classification	0.27	0.46	0.27
Wet scrubbing	0.27	0.46	0.27
Crush scrubbing	0.25	0.35	0.4
Multi-crush scrubbing	0.25	0.40	0.35
Mechanical crushing	0.2	0.2	0.6

Classes H, M and L are high, medium and low quality aggregate respectively.
 R_{RCA} =recycled coarse aggregate and R_{RFA} =recycled fine aggregate.

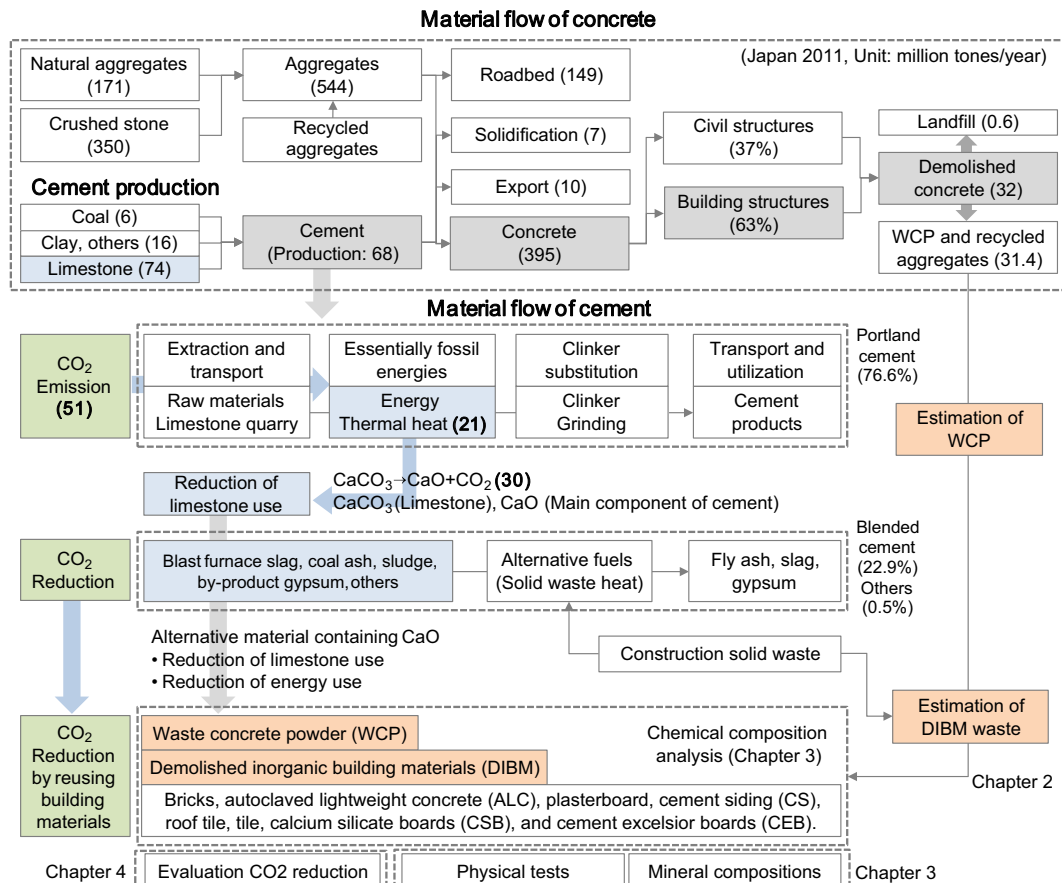


Fig. 2. CO₂ reduction by reusing DIBM and WCP in simplified cement fabrication process.

Table 3
Estimation method of DIBM waste.

Step	Procedure	Subject	Remarks
1	Shipments investigation	8 Kinds of materials	Brick, ALC, roof tile, plaster board, CS, Tile, CSB, CEB
2	Constructed area	4 Kinds of structures	Wooden structure (WS) Reinforced concrete (RC) Steel reinforced concrete (SRC) Steel structure (SS) etc. structures (etc.)
		2 Kinds of uses	Residence (R), non-residence (NR)
3	Regression analysis	Input units of building materials	Estimation with building structure and use
4	Building life estimation	Building service life	Estimation of demolition period in WS-R, RC-R, SRC-NR, S-R and S-NR
5	Demolition work	Wastes output	Estimation of each DIBM waste

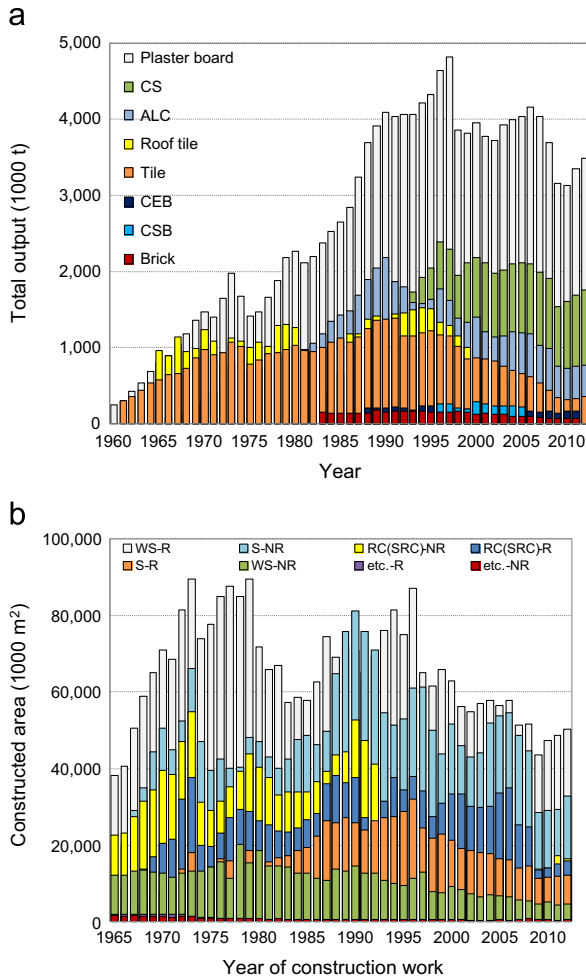


Fig. 3. Total output and constructed area of inorganic building materials (IBM). (a) Total output of the IBM and (b) constructed area of IBM with building structures and uses.

Therefore, if DIBMs are used as a cement substitute material, it is expected that the quantity of waste to be disposed of, and the use of natural materials such as limestone will be reduced, as will CO₂ emissions during cement production [31,32]. This study proposed four mixing proportions for recycled cement using DIBMs as a cement substitute material, and a performance evaluation was conducted. Additionally, this study analyzed CO₂ reduction effects in the cement industry by usage of the proposed recycled cement. Fig. 2 illustrates a schematic diagram of CO₂ reduction brought about by reusing DIBMs and WCP in the cement fabrication process used in this study.

2. Estimation of DIBM waste

There is currently a large demand for DIBMs that have a chemical composition similar to that of cement. In addition, because recycling methods that utilize heat processing, such as calcination, are sensitive to the chemical components of raw materials, DIBMs with chemical components that can be identified in advance can be used as cement substitute materials [33–36]. This study estimated the quantity of various kinds of DIBMs that can be used as cement substitute materials for cement production in Japan.

2.1. Estimation method

To estimate the amount of waste in a construction area, this study calculated the input unit of construction materials in the area and the shipments per construction material. It also estimated the life cycle of the building and calculated the quantity of input materials based upon the dismantlement of the structure [37]. In particular, this study focused on eight kinds of inorganic construction materials: bricks, autoclaved lightweight concrete (ALC), roof tile, plasterboard, cement siding (CS), tile, calcium silicate boards (CSB), and cement excelsior boards (CEB). Table 3 presents the DIBM waste estimation method.

2.2. Estimation of the amount of waste generated

2.2.1. Input units of building materials

Construction materials differ in their properties and thus, specific materials are selected based upon building structure and use. Many of these vary with regard to the life of the material [20,38]. Accordingly, it is necessary to identify the percentage of construction materials, along with building type, in order to estimate the quantity of waste produced during building demolition. Such an estimate is based upon the emission quantity of the construction materials. This study defined the input quantity of construction material per unit area of a building as the input unit of building material, which was obtained from the relationship between the annual emission quantity of each material and the constructed area per structure and use. Fig. 3 shows the constructed area per structure and use and the emission quantity of inorganic building materials in Japan during a period of 50 years.

To estimate the quantity of waste from calculation of the input unit, we conducted a simple regression analysis using the object variable as the emission quantity of construction materials, and the explanatory variable as the constructed area of eight kinds of construction material. Fig. 4 shows the relationship between the output of DIBM in a wooden structure (residence) as an example. In addition, the explanatory variable with a coefficient of determination less than 0.3 from simple regression analysis was excluded

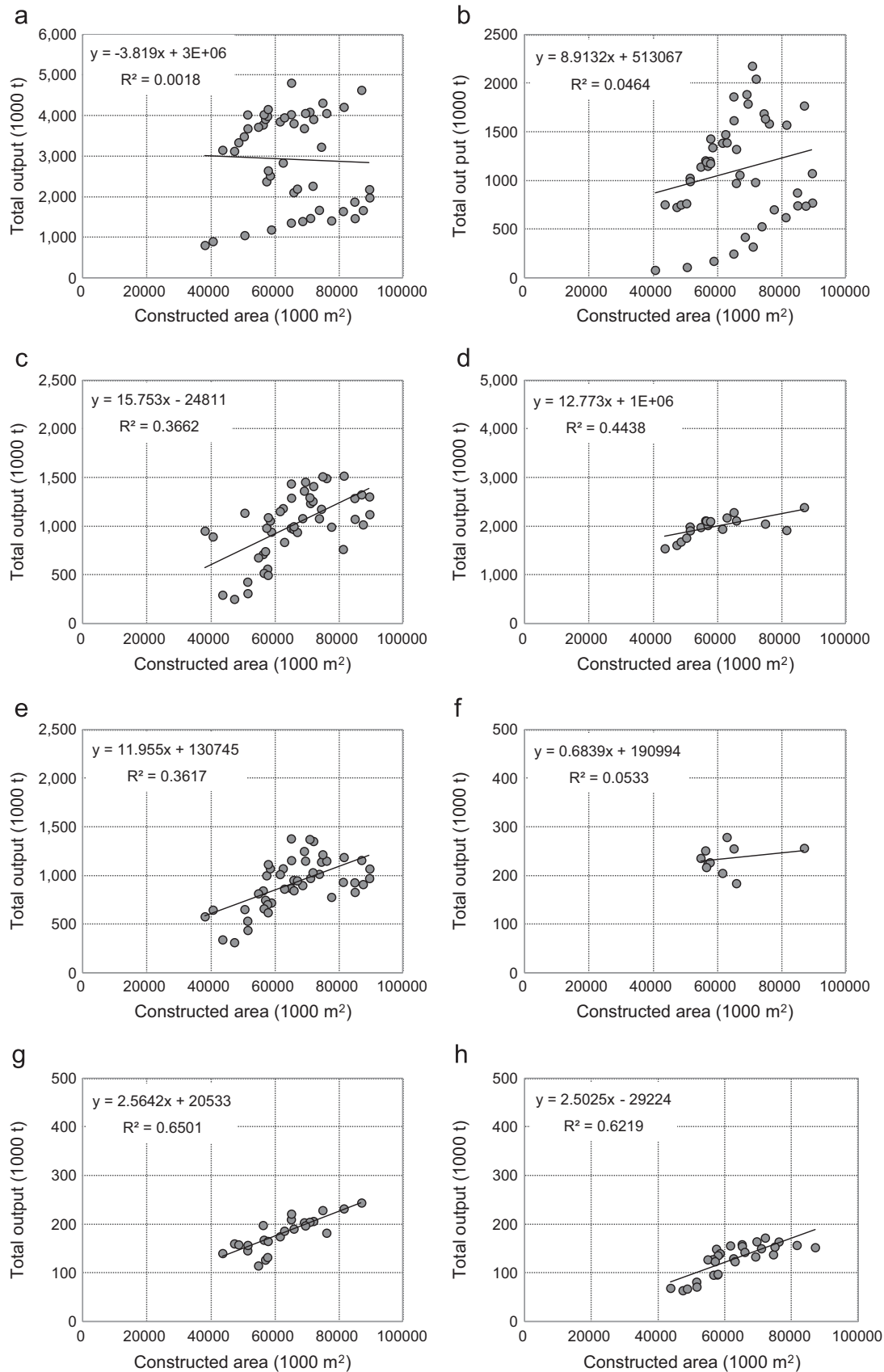


Fig. 4. Relationship between output of DIBM in wooden structure (residence). (a) Plaster board, (b) ALC, (c) roof tile, (d) CS, (e) tile, (f) CSB, (g) CEB and (h) brick.

from multiple regression analysis, based on the assumption that it was not related to the object variable. Finally, explanatory variables for three types of buildings – WS-NR, etc.-R, and etc.-NR –

as shown in Table 3 were excluded from the analysis as they exhibited values that were much lower than the constructed area of other explanatory variables.

Table 4
Multiple regression analysis results for bricks.

Independent variable	$R^2 = 0.9417$		$R^2 = 0.9452$	
	Coefficient (input units)	p-Value (before correction)	Coefficient (input units)	p-Value (after correction)
WS-R	0.4906	0.3834	1.4832	0.0000
RC-R, SRC-R	−0.0231	0.9788	–	–
RC-NR, SRC-NR	0.7771	0.1744	1.2503	0.0024
S-R	3.4216	0.0413	–	–
S-NR	0.0679	0.8885	–	–

Table 5
Input units of inorganic building materials.

Classification	Inorganic building materials							
	Brick	ALC	Roof tile	Plaster board	CS	Tile	CSB	CEB
	1	2	3	4	5	6	7	8
WS-R	1.483	–	7.359	–	19.06	–	–	5.895
RC-R, SRC-R	–	–	–	–	–	–	7.288	–
RC-NR, SRC-NR	1.250	–	16.95	162.4	–	17.14	–	–
S-R	–	63.61	–	–	–	21.51	–	–
S-NR	–	–	–	–	18.62	–	–	–

Multiple regression analysis was conducted using an explanatory variable with R^2 greater than 0.3 to verify its correlation through a null hypothesis. As a judgment criterion, the null hypothesis is abandoned and a multiple regression equation is deemed meaningful when the p -value is under 0.05. If there is an explanatory variable that has a p -value higher than 0.05 and the null hypothesis is not abandoned, multiple regression analysis is conducted until the null hypothesis is denied as the p -value of all items falls below 0.05. This is accomplished by excluding it from the explanatory variables with a higher p -value in order to gradually reduce any explanatory variable [39–41]. Table 4 shows the analysis result for bricks, and Table 5 shows the input units of building materials obtained from multiple regression analysis of eight kinds of inorganic building materials.

2.2.2. Estimation of the service life of a building

The service life of a structure was estimated with the statistical analysis method using observation data up to an elapsed time of 50 years [37]. The residual ratio $R(t)$ was obtained using Eqs. (1)–(3) from the number of buildings (dismantled) disposed of in the year 2005 and the existing number of buildings as of January 1, 2005. This study assumed the period of time when the residual ratio reaches 0.5 to be the average life span, and this was used as the lifetime prediction value.

In addition, we assumed that the residual ratio of the building follows the Weibull distribution shown in Eq. (4). This study estimated the parameter associated with 100 years of elapsed time and performed a statistical analysis. As an example, Fig. 5 shows the results of a life span estimation of each structure. Overall, in 2005 the estimates were as follows: WS-R, 54.61 years; RC-R, 54.07 years; RC-NR, 51.80 years; S-R, 50.80 years; and SS-NR, 43.38 years.

$$E(t) = B(t)/A(t) \quad (1)$$

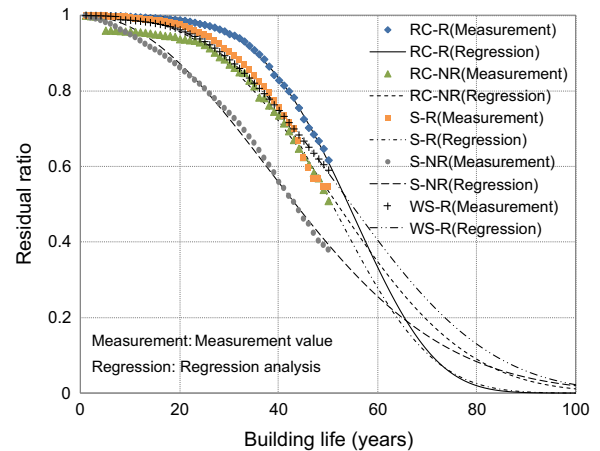


Fig. 5. Building life prediction of each structure.

$$S(t) = 1 - E(t) \quad (2)$$

Table 6
Estimation method of annual eliminated area.

Year	Calculation
1965	$A_0 = 0$
1966	$A_1 = S_0(R_0 - R_1)$
1967	$A_2 = S_0(R_1 - R_2) + S_1(R_0 - R_1)$
1968	$A_3 = S_0(R_2 - R_3) + S_1(R_1 - R_2) + S_2(R_0 - R_1)$
⋮	⋮
(1965 + n)	$A_n = S_0(R_{n-1} - R_n) + S_1(R_{n-2} - R_{n-1}) + S_2(R_{n-3} - R_{n-2}) + \dots + S_{n-1}(R_0 - R_1)$

A (eliminated area), S (constructed area), R (residual ratio), and n (year).

$$R(t) = R(t-1)S(t) \quad (3)$$

$$R(t) = \exp[-(t/\eta)^m] \quad (4)$$

where $A(t)$ – number of existing buildings, $B(t)$ – number of demolished buildings, $E(t)$ – rate of building demolition, $S(t)$ – residual ratio in section, $R(t)$ – residual ratio, t – elapsed time, m – shape parameter, and η – criterion parameter.

2.2.3. Estimation of waste quantity

The annually demolished area was first calculated using the residual ratio obtained in Eq. (4), with the process as shown in Table 6. In addition, the quantity of waste was calculated according to Eq. (5) with the input unit of construction materials and demolished floor area, and the results of the estimated quantity

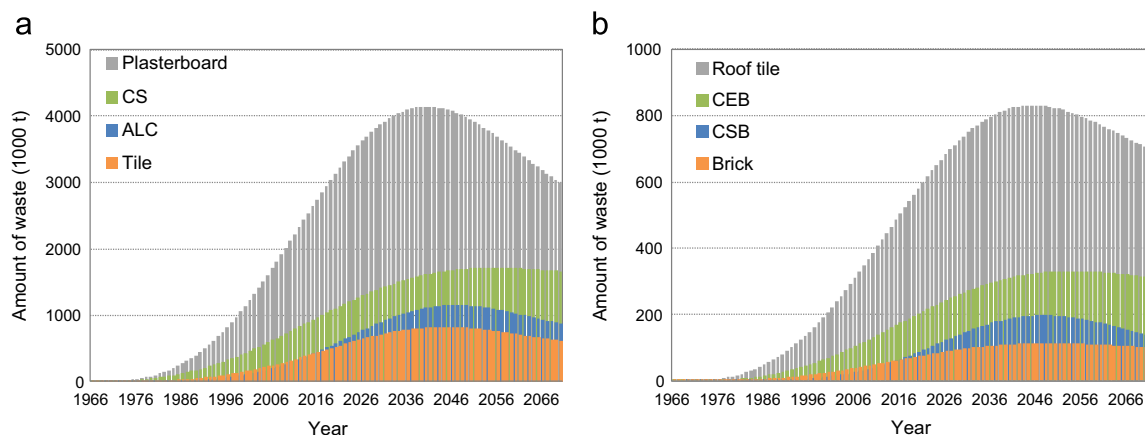


Fig. 6. Prediction of DIBM waste. (a) Plasterboard, CS, ALC and Tile and (b) roof tile, CEB, CSB and brick.

Table 7

Chemical composition analysis of DIBM.

	Ig.loss	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	TiO ₂	Total
WCP	15.95	35.68	9.78	3.94	29.21	2.23	0.78	1.66	0.72	0.4	100.3
Brick	0.25	64.66	19.02	6.96	1.14	1.47	0.08	2.23	2.28	0.67	98.76
ALC	11.4	47.9	2.6	2.4	32.8	–	2	0.05	0.3	–	99.45
Roof tile	–	49.33	22.36	15.94	1.84	–	–	–	7.89	2.63	99.99
CS, CEB	18.53	9.6	10.5	54.77	–	1.37	–	2.48	2.75	100	–
Tile	–	46.83	18.22	3.32	24.59	–	–	–	3.13	2.6	98.69
CSB	23.17	30.48	1.24	0.79	39.87	0.43	0.5	0.09	0.16	0.07	96.8
Lime stone	53.18	0.26	0.04	0.02	45.03	0.42	0	0.01	0.04	0.04	99.04

Table 8

Proposed material compositions using inorganic building materials.

Trial products		Chemical composition (wt%)										
Mix proportion	Material composition	Ig.loss	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	TiO ₂	Total
Mix 1	WCP	6.22	13.92	3.81	1.54	11.39	0.87	0.3	0.65	0.28	0.16	39.13
	Lime stone	32.44	0.16	0.02	0.01	27.47	0.26	0	0.01	0.02	0.02	60.41
	OPC-type 1	–	23.03	6.28	2.53	63.59	1.84	0.5	1.07	0.5	0.3	100
Mix 2	CS	0	3.71	1.92	2.1	10.95	0	0.27	0	0.5	0.55	20
	CSB	11.59	15.24	0.62	0.4	19.94	0.22	0.25	0.05	0.08	0.04	36.87
	Lime stone	15.95	0.08	0.01	0.01	13.51	0.13	0	0	0.01	0.01	24.39
	OPC-type 4	–	26.96	3.62	3.54	62.91	0.48	0.74	0.07	0.83	0.85	100
Mix 3	CSB	12.65	0.51	0.33	16.55	0.18	0.21	0.04	0.07	0.03	40.18	–
	Brick	0.01	3.23	0.95	0.35	0.06	0.07	0	0.11	0.11	0.03	4.94
	Lime stone	27.65	0.14	0.02	0.01	23.42	0.22	0	0.01	0.02	0.02	51.5
	Oxidized steel	–	–	–	1.5	–	–	–	–	–	–	1.5
Mix 4	OPC-type 5	–	26.25	2.44	3.58	65.58	0.77	0.35	0.25	0.33	0.14	100
	ALC	2.05	8.62	0.47	0.43	5.9	0	0.36	0.01	0.05	0	17.9
	Tile	0	4.68	1.82	0.33	2.46	0	0	0	0.31	0.26	9.87
	CS	0	1.85	0.96	1.05	5.48	0	0.14	0	0.25	0.28	10
	Lime stone	32.97	0.16	0.02	0.01	27.92	0.26	0	0.01	0.02	0.02	61.4
	OPC-type 1	–	23.88	5.1	2.85	65.09	0.41	0.77	0.02	1	0.87	100

of DIBM waste are shown in Fig. 6. As a result, the quantity of waste was estimated using construction material input values, and the estimates of building service life presented in Sections 2.2.1 and 2.2.2:

$$W_n = A_n U \quad (5)$$

where W denotes the quantity of waste, U represents the input units of building materials, A is the eliminated area and n is the number of IBM (shown in Table 5).

3. Manufacturing of cement with DIBM as substitute materials and performance evaluation

This study proposes material compositions for cement manufacturing when using DIBM as a cement substitute material. In addition, a chemical component analysis of DIBMs was conducted to reduce the CO₂ emission from the decarbonation reaction of limestone in the cement calcination process, through usage of DIBMs. Among these mix proportions, two kinds of cement trial products (recycled cement), using WCP, CSB, and brick as cement

substitute materials, were produced, and their performance was evaluated through mortar tests.

Table 9

Mineral composition of recycled cement by Bogue's equation (wt%).

	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	Total
Mix 1 (OPC-type 1)	50.4	28.1	12.4	7.7	98.6
Mix 2 (OPC-type 4)	36.4	49.9	3.6	10.8	100.7
Mix 3 (OPC-type 5)	60.1	30	0.4	10.9	101.4
Mix 4 (OPC-type 1)	58	24.8	8.7	8.7	100.2

3.1. Proposal and manufacturing of material combinations of recycled cement

DIBMs have similar chemical components because the percentage of material is fixed, therefore, the chemical composition of DIBMs needs to be analyzed. Table 7 shows the chemical component analysis results of the eight kinds of DIBMs covered in this study, as well as limestone, one of the main materials of Ordinary Portland Cement (OPC) used as a natural resource. This study examines the chemical components of IBMs and proposes four types of mix proportions in recycled cement, as shown in Table 8.

Table 9 shows the results of the mineral composition estimations of four types of recycled cement, calculated theoretically by Eqs. (6)–(10) of Bogue [42,43] from the chemical analysis

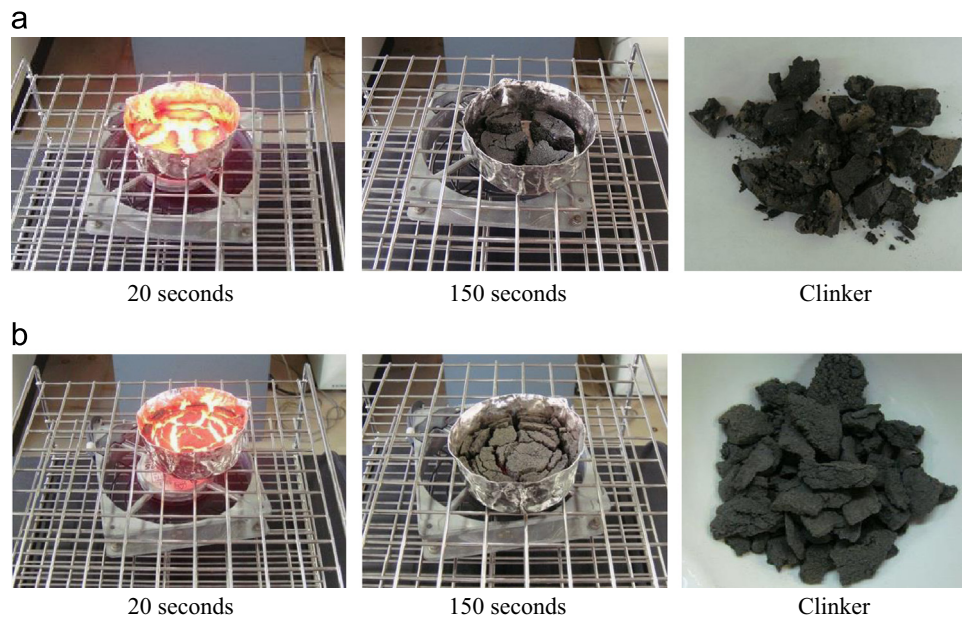


Fig. 7. Manufacturing process of recycled cement. (a) Case of Mix 1 (WCP + Lime stone) and (b) case of Mix 3 (CSB + Brick + Lime stone + Oxidized steel).

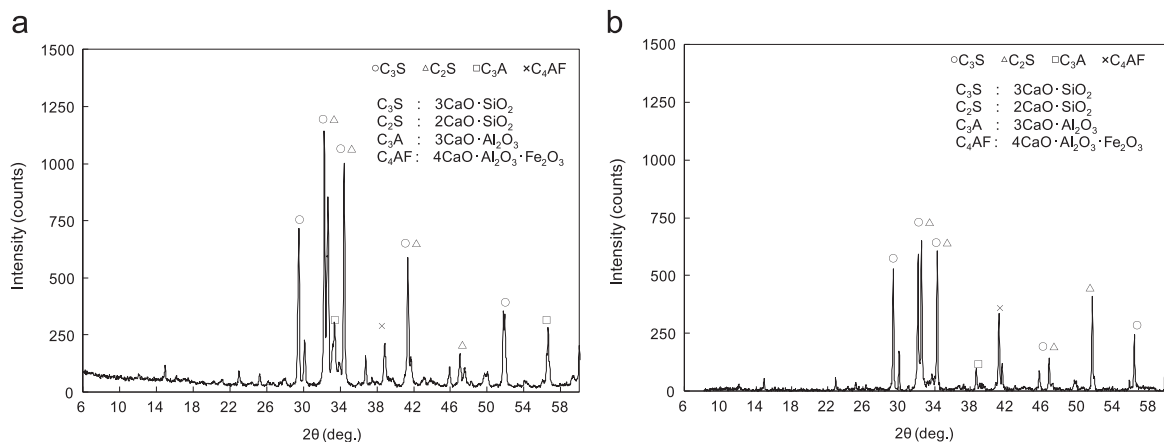


Fig. 8. XRD analysis results of clinkers. (a) Case of Mix 1 and (b) case of Mix 3.

Table 10

Properties of trial products of recycled cement.

	Material	Alkali (%)	Free-CaO (%)	Color	Density (g/cm ³)
Mix-1 (OPC-type 1)	WCP (39%), lime stone (61%)	1.4	0.70	Yellow	3.05
Mix-3 (OPC-type 5)	CSB (41.5%), lime stone (52%), brick (5%), oxidized steel (1.5%)	0.47	0.18	Gray	3.09

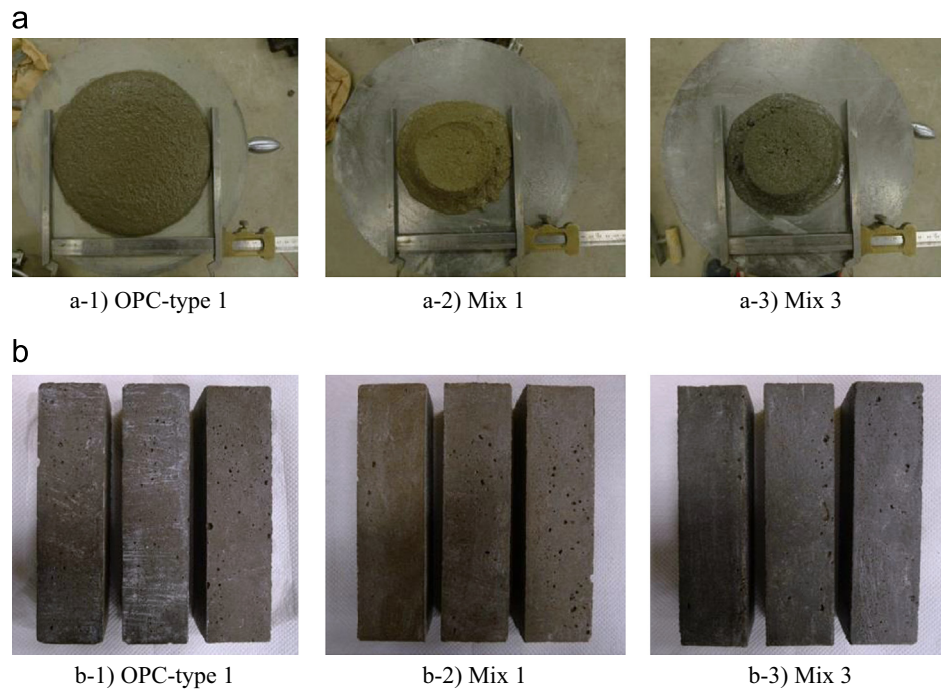


Fig. 9. Flow test and specimen cement mortar. (a) Flow test and (b) specimen.

Table 11
Test results of mortar compressive strength.

Specimens	Mortar flow (cm)	Compressive strength (MPa)			
		3 Days	7 Days	28 Days	91 Days
OPC-type 1	20.1	24.1	30.7	43.3	52.3
Mix 1	14.2	13.2	27.8	43.7	49.9
Mix 3	14.2	9.8	14.7	27.3	43.7

Table 12
WCP input rate calculation method in production of recycled cement.

Step	Procedure	Subject	Remarks
1	Chemical composition of WCP	Range of C/S (CaO/SiO ₂) (0.4–1.1)	C/S is 0.82 of WCP in this study
2	Chemical composition of market cement	OPC-type 1 (C/S 3.11)	Supplement contents of CaO with addition of limestone
3	Input of WCP	Percentage of WCP	$\frac{x\text{CaO}_{\text{WCP}} + (1-x)\text{CaO}_{\text{Lime}}}{x\text{SiO}_2\text{WCP}} = 3.11 \quad (16)$ <p> x: WCP input percentage CaO_{WCP}: CaO contents of WCP CaO_{Lime}: CaO contents of limestone SiO_{2WCP}: SiO₂ contents of WCP </p>

Assumption for calculation of material input rate.

CaO contents of limestone is 56%.

Al₂O₃ and Fe₂O₃ are enough in contents as included in WCP.

CaO + SiO₂ contents of WCP are 70%.

WCP and lg.loss of limestone are 15% and 44% respectively.

presented in Tables 7 and 8.

$$C_3S = 4.07 \times \text{CaO} - (7.60 \times \text{SiO}_2 + 6.72 \times \text{Al}_2\text{O}_3 + 1.43 \times \text{Fe}_2\text{O}_3 + 2.85 \times \text{SO}_3) \quad (6)$$

$$C_2S = 2.87 \times \text{SiO}_2 - 0.754 \times C_3S \quad (7)$$

$$C_3A = 2.65 \times \text{Al}_2\text{O}_3 - 1.69 \times \text{Fe}_2\text{O}_3 \quad (8)$$

$$C_4AF = 3.04 \times \text{Fe}_2\text{O}_3 \quad (9)$$

$$\text{CaSO}_4 = 1.70 \times \text{SO}_3 \quad (10)$$

In addition, two types (Mixes 1 and 3 in Table 8) of recycled cement were produced experimentally, and the experimental process is shown in Fig. 7.

3.2. Performance evaluation of recycled cement

3.2.1. Chemical features of recycled cement

To identify the clinker mineral composition of recycled cement, XRD (X-ray diffraction) analysis was conducted, and the results are shown in Fig. 8. The analytical results of Mix 1 using WCP showed peaks in the primary minerals present in cement, such as C₂S, C₃A,

C_4AF , and C_3S , the latter of which has the most significant influence on the hydraulicity of cement. In the case of Mix 3, the content of Al_2O_3 was restricted when designing the combination of cement materials such that the C_3A peak was not observed in the XRD results.

As well, measurement of the free- CaO quantity in cement is important for determinations of the performance of cement, because high free- CaO content causes cracks in the cement. The free- CaO content of the cement compositions was measured in compliance with quantification of free calcium oxide [44]. The free- CaO amount was found to be 0.7% and 0.18%, respectively, confirming the usability of these mixtures as recycled cement.

3.2.2. Physical features of recycled cement

The density of recycled cement using WCP was 3.05 g/cm^3 , with this result being lower than the standard value of 3.14 g/cm^3 of Portland cement [45,46]. This is because the elemental percentages of Al_2O_3 and SiO_2 , which have relatively low specific gravities, were comparatively high. Conversely, recycled cement using CSB and brick recorded a density of 3.09 g/cm^3 , which is slightly higher than that of the recycled cement using WCP. This is because the Al_2O_3 content was restricted and the amount of Fe_2O_3 increased. In summary, the physiochemical features of the two recycled cement types produced by this experiment can be summarized as shown in Table 10.

Table 13
Material input for recycled cement manufactured by C/S ratio of WCP.

C/S ratio	Chemical composition of WCP (wt%)		Material composition of cement (wt%)		Material input per 1 t of cement (kg)	
	CaO_{WCP}	SiO_{2WCP}	WCP	Lime stone	WCP	Lime stone
0.4	20.0	50.0	29.2	70.8	453.5	1097.3
0.5	23.3	46.7	31.5	68.5	483.2	1052.2
0.6	26.3	43.8	33.8	66.2	513.3	1006.6
0.7	28.8	41.2	36.1	63.9	542.6	962.1
0.8	31.1	38.9	38.4	61.6	572.0	917.6
0.9	33.2	36.8	40.8	59.2	601.2	873.2
1.0	35.0	35.0	43.1	56.9	629.5	830.2
1.1	36.65	33.4	45.5	54.5	657.6	787.6

3.2.3. Mechanical properties of produced mortar using recycled cement

For analysis of the effectiveness of the two kinds of recycled cement, their mechanical properties were evaluated through mortar specimen tests [47]. The OPC-1 type, which is available on the market, recycled cement (Mix 1, Table 8) using WCP, and recycled cement (Mix 3, Table 8) using CSB and brick were used to produce the test specimens. Three mortar specimens with dimensions of $4 \times 4 \times 16 \text{ cm}^3$ were produced using each cement type. These were mixed at the ratio of water:cement:standard sand = 1:2:6, and all specimens were set in water and cured at 20°C . The samples were evaluated with a flow test (Fig. 9a) in an unhardened state and a compressive strength test of the specimen (Fig. 9b) after hardening, the results of which are shown in Table 11. The mortar specimens composed of recycled cement displayed a high compressive strength, as did the general cement mortar.

4. CO_2 reduction by the production of recycled cement

4.1. Estimation of the producible amounts of recycled cement

4.1.1. Producibile recycled cement with WCP (Mix 1)

The WCP input rate was calculated as shown in Table 12. The quantity of material input was obtained according to the calculation method of Table 12 for the produced amount of cement using WCP, taking into account the difference in chemical components from DIBMs as shown in Table 13. In addition, because the discharge quantity of WCP differs depending on the percentage of recycled concrete waste as recycled aggregates, and the percentage of WCP discharge from production of recycled aggregates, the

Table 14
Material input for recycled cement manufactured by Mix 2.

Material composition of cement (wt%)			Material input per 1 t of cement (kg)		
CS	CSB	Lime stone	CS	CSB	Lime stone
20	50	30	276.0	690.0	414.0

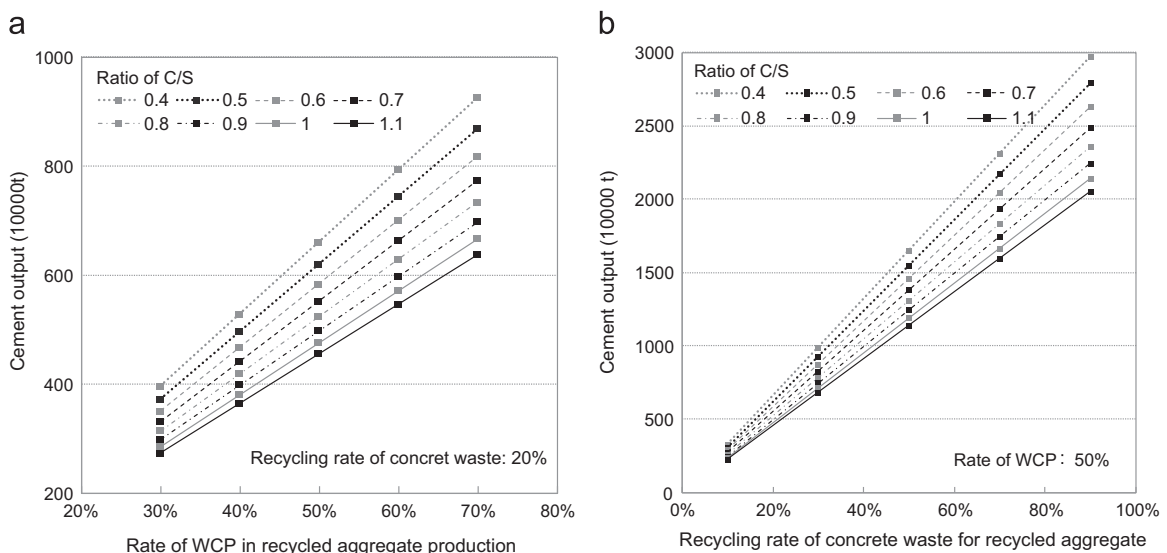


Fig. 10. Producibile cement output according to recycling rate and WCP rate (Mix 1). (a) Cement output by WCP rate and (b) cement output by Recycling rate.

producible quantity of cement was estimated with the modification of these two factors.

Because the amount of added limestone increases and the input amount of WCP decreases if C/S is small, the producible quantity of recycled cement from the same quantity of WCP will increase. In addition, the producible quantity of recycled cement increases as the discharge quantity of WCP increases from the production of recycled aggregates, and the recycling rate of concrete waste also increases as recycled aggregates increase.

For example, when the recycling rate of concrete waste as recycled aggregates is 20%, the discharge percentage of WCP from production of recycled aggregates is 50% and C/S is 0.8, the production quantity of cement is about 5,250,000 t, which corresponds to about 9.1% of annual cement production (about 57,580,000 t) in Japan as of 2012 [25]. Fig. 10 shows the generated quantity of WCP and the producible quantity of recycled cement using WCP as a cement substitute material.

4.1.2. Producible recycled cement with CS and CSB (Mix 2)

Table 14 shows the material input quantity of cement production using Mix 2. Fig. 11 shows the results. Production of cement by Mix 2 required 50% CSB and 20% CS, showing that the input quantity of CSB is 2.5 times higher than that of CS. When comparing the maximum waste quantities, CSB was calculated to be 198,000 t while a value of 1,715,000 t was obtained for CS. Therefore, the waste quantity of CS is 8 times greater than that of CSB. From the CSB waste estimates, the cement production quantity indicated in Fig. 11 was determined. The maximum amount of producible recycled cement was calculated to be 287,000 t, corresponding to about 0.5% of annual cement production in Japan.

4.1.3. Producible recycled cement with CSB, brick, and oxidized steel (Mix 3)

Table 15 shows the material input of cement production using Mix 3. Input values of 41.5% CSB and 5% brick were estimated for Mix 3, showing that the input quantity of CSB is over eight times that of brick. When comparing the maximum waste quantities, calculated values of 198,000 t of CSB and 113,000 t of brick were obtained but because the input difference was large, the cement production quantity shown in Fig. 11 was determined from the results of the waste quantity determinations of CSB. The maximum

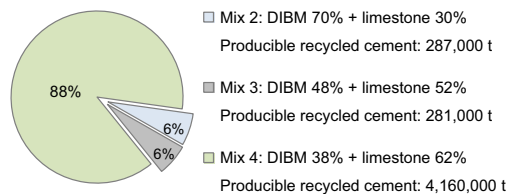


Fig. 11. Producible cement output using Mix-2, Mix-3 and Mix-4.

Table 15
Material input for recycled cement manufactured by Mix 3.

Material composition of cement (wt%)				Material input per 1 t of cement (kg)			
CSB	Brick	Lime stone	Oxidized steel	CSB	Brick	Lime stone	Oxidized steel
41.5	5	52	1.5	680	81.9	852.1	24.6

amount of producible cement was 281,000 t, corresponding to about 0.5% of annual cement production in Japan.

4.1.4. Producible recycled cement with ALC, tile, and CS (Mix 4)

Table 16 shows the material input quantity of recycled cement production using Mix 4. Cement production by Mix 4 showed percentages of 18% ALC, 10% tile, and 10% CS. When comparing the maximum waste quantities, values of 1,153,000 t of ALC, 822,000 t of tile, and 1,715,000 t of CS were calculated. Cement production likely depends on the waste quantity of ALC or tile. The maximum amount of producible cement was 4,160,000 t, corresponding to about 7.2% of annual cement production in Japan. The quantity of cement produced with Mix 4 is higher than those of Mix 2 or Mix 3 as shown in Fig. 11.

4.2. Quantity of CO₂ emissions from production of recycled cement

CO₂ emissions from the cement production process in Japan constitute 0.725 t for 1 t of cement production, and exert a considerable environmental influence. The main sources of generated CO₂ include fossil fuels used for decarbonation of limestone in the calcination process, use of electric energy, and transportation emissions (58%, 31%, and 11%, respectively). This study calculated the CO₂ emission from the recycled cement production process, and compared it with the CO₂ quantity generated by the production process of cement on the market. Assuming that the calcination fuel and electricity demands, calcination temperature, and calcination processing times are the same for the production of both cement types, we evaluated the CO₂ emissions from the decarbonation reaction of limestone.

4.2.1. Recycled cement with WCP (39%) and limestone (61%)

The CO₂ emission from the decarbonation reaction of limestone was calculated from Eq. (12), according to the quantity of limestone applied to 1 t of recycled cement using WCP (39%) and limestone (61%) (Table 13). The results are presented in Table 17, and the amount of limestone necessary for the production of 1 t of ordinary cement is 1160 kg.

$$\text{CO}_{2\text{Lime}} = M_{\text{Lime}}(44/100) \quad (11)$$

Table 16
Material input for recycled cement manufactured by Mix 4.

Material composition of cement (wt%)				Material input per 1 t of cement (kg)			
ALC	Tile	CS	Lime stone	ALC	Tile	CS	Lime stone
18	10	10	62	277.0	153.9	153.9	954.2

Table 17
CO₂ emission in calcinations for 1 t of cement production (unit: kg).

C/S ratio	Material input per 1 t of cement		CO ₂ emission in limestone calcination	
	Recycled cement	Portland cement	Recycled cement	Portland cement
0.4	1097.3	1160	482.8	510.4
0.5	1052.2		463.0	
0.6	1006.6		442.9	
0.7	962.1		423.3	
0.8	917.6		403.7	
0.9	873.2		384.2	
1.0	830.2		365.3	
1.1	787.6		346.5	

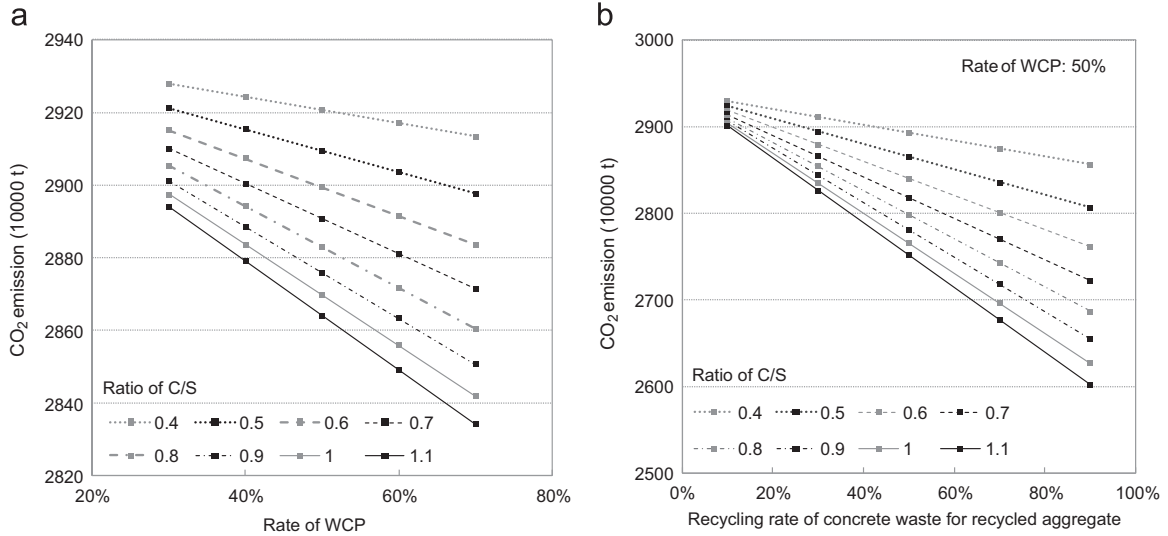


Fig. 12. CO₂ emission reduction of recycled cement according to recycling rate and WCP rate (Mix-1). (a) Ratio of C/S in WCP (b) recycling rate of concrete waste.

Because the amount of applied limestone decreases as the C/S ratio of WCP increases, the CO₂ quantity emitted from the decarbonation reaction of limestone is reduced in cement production. This paper estimated the CO₂ emission by the C/S ratio and the generated amount of WCP using the above results. The findings are presented in Fig. 12. Japan produces 57,580,000 t of cement every year using existing natural materials. The resultant CO₂ emission, when using only natural materials, was 29,389,000 t, and the CO₂ reduction effect, caused by an increase in the generated amount of WCP, increased as the C/S ratio increased. For example, when the recycling rate of concrete waste as recycled aggregates is 20%, the fine powder discharge rate from the production of recycled aggregates is 50%, and the C/S ratio is 0.8, there is a reduction effect of CO₂ corresponding to about 560,000 t.

The CO₂ emission from recycled cement (Fig. 7a) in this study was evaluated. The quantity of limestone and WCP applied to the production of 1 t of recycled cement by Mix 1 was 957.6 and 612.3 kg, respectively. The CO₂ emission from each material was dependent on their input quantities. CaO in concrete is present in four states – calcium silicate hydroxide (CSH), calcium hydroxide [Ca(OH)₂], calcium sulfo-aluminate (CSA), and non-hydrated clinker particles. Because these react with CO₂ in air and dissolve to become CaCO₃, this analysis considered the CO₂ amount included in WCP.

The CO₂ emissions from limestone in market cement and recycled cement can be obtained using Eqs. (12) and (13). While the CaO percentage in ordinary limestone was 56%, the CaO content in limestone used for this study was 45% due to moisture effects (Table 7). When calculating the CO₂ emission from the limestone used in recycled cement, the modification factor (45/56=0.804) was multiplied by M_{Lime} . The CO₂ emission from the WCP of recycled cement was then calculated from Eq. (14), and the total CO₂ emission of WCP was calculated from Eq. (15). To calculate CO₂Recycled Cement–WCP of Eq. (14), a thermogravimetric and differential thermal analyzer (TG-DTA) was utilized. As a result, it was found out that 1.14% of CO₂ from WCP was discharged by the decarbonation reaction of CaCO₃ that occurred at about 700 °C.

$$\text{CO}_{2\text{Market-Lime}} = M_{\text{Market-Lime}}(44/100) \quad (12)$$

$$\text{CO}_{2\text{Recycled Cement-Lime}} = 0.804 \times M_{\text{Recycled Cement-Lime}}(44/100) \quad (13)$$

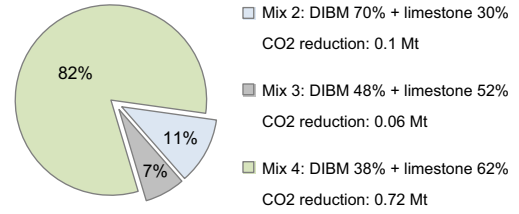


Fig. 13. CO₂ emission reduction of recycled cement (Mix-2, Mix-3 and Mix-4).

$$\text{CO}_{2\text{Recycled Cement-WCP}} = M_{\text{Recycled Cement-WCP}} 1.14 (\%) \quad (14)$$

$$\text{CO}_{2\text{Recycled Cement}} = \text{CO}_{2\text{Recycled Cement-Lime}} + \text{CO}_{2\text{Recycled Cement-WCP}} \quad (15)$$

4.2.2. Recycled cement with CS (20%), CSB (50%), and limestone (30%)

Because neutralization by absorption of CO₂ rarely occurs in DIBMs used in Mix 2, CO₂ generation by calcination was limited to limestone. The recycled cement in Mix 2 had a CO₂ reduction effect of about 71.3%. In annual cement production in Japan, however, the CO₂ emissions reduction that can be achieved by the production of recycled cement is only 104,000 t, as shown in Fig. 13. This has a trivial effect overall on the cement industry because the producible amount of cement is low, due to the small amounts of CS and CSB waste.

4.2.3. Recycled cement with CSB (41.5%), brick (5%), limestone (52%), and oxidized steel (1.5%)

The recycled cement production process using Mix 3 had a CO₂ reduction effect of about 40.9%. Up to 61,000 t of CO₂ can be reduced when producing recycled cement from Mix 3, as compared to 29,389,000 t of CO₂ emission using natural materials as shown in Fig. 13.

4.2.4. Recycled cement with ALC (18%), tile (10%), CS (10%), and limestone (62%)

Fig. 13 shows also the calculated estimates of the annual CO₂ emission from the decarbonation reaction according to the amount of limestone applied to 1 t of recycled cement using Mix 4.

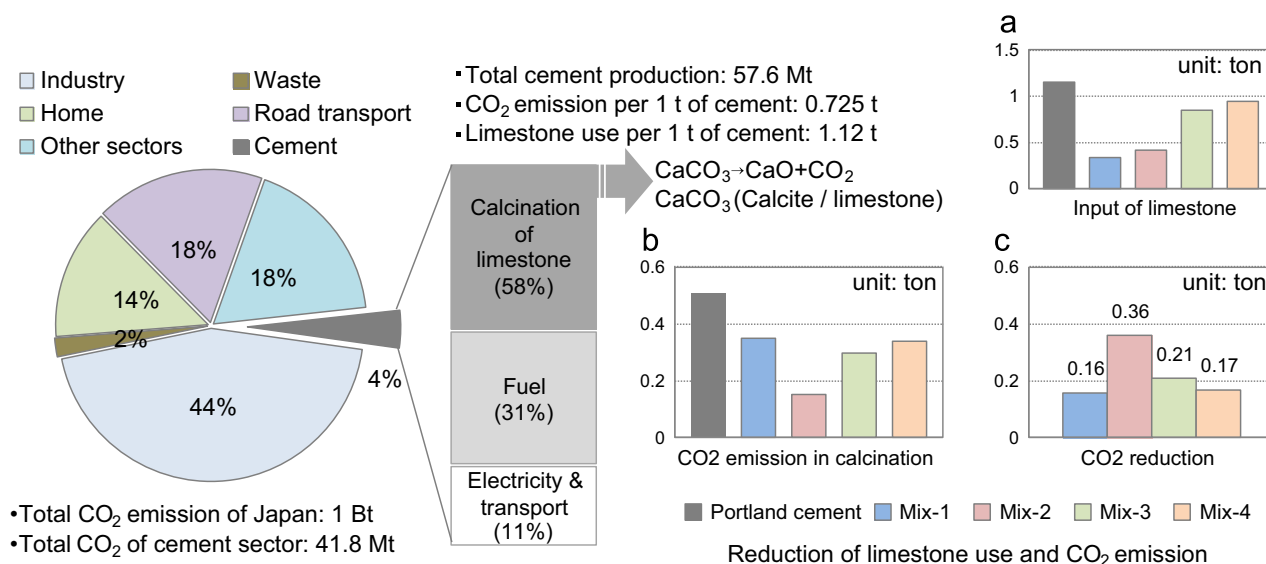


Fig. 14. CO₂ emission reduction in calcinations by using DIBM [48].

Cement production using Mix 4 had a CO₂ reduction effect up to 720,000 t/year.

Finally, the input of limestone, the CO₂ emission in calcinations and CO₂ emission reduction of recycled cement by using DIBMs are shown in Fig. 14.

5. Conclusions

This study proposed a recycling method for recycled cement using DIBMs and WCP as cement substitute materials, and the properties of trial recycled cement were evaluated. To estimate the amount of DIBMs and WCP, the service life of a structure was estimated with a statistical analysis method using observation data up to an elapsed time of 50 years for waste generated in Japan. As a result, this study proposed material compositions for recycled cement when using DIBMs and WCP as cement substitute materials. The suggested mix proportions were WCP (Mix 1), CS and CSB (Mix 2), CSB, brick, and oxidized steel (Mix 3), and ALC, tile, and CS as input materials (Mix 4). Two kinds of recycled cement using Mix 1 and Mix 3 were manufactured experimentally as trial products, and their mechanical properties were evaluated through mortar evaluation. The mortar specimens using recycled cement presented high compressive strengths, as did the general cement mortar.

Additionally, the CO₂ reduction effects in the cement industry by usage of the proposed recycled cement were analyzed. The CO₂ emission from the cement production process in Japan is 0.725 t for 1 t of cement production, which has a considerable influence

on the environment. This study calculated the CO₂ emission from the recycled cement production process, and compared it with the CO₂ quantity generated by the production process of cement on the market. Assuming that the calcination fuel and electricity demands, calcination temperature, and calcination processing times are the same, we evaluated the CO₂ emission from the decarboxylation reaction of limestone. The producible recycled cement ranged from 0.5% to 9.1% of the annual cement production (about 57.6 million tons) in Japan. Additionally, the CO₂ reduction effects by usage of recycled cement varied from 0.06 million tons to 0.72 million tons, from the total annual cement CO₂ emission of about 29.4 million tons with use of natural limestone resources in Japan.

Acknowledgment

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Appendix A

See Tables A1 and A2.

Table A1

Cement sales by type in Japan (unit: million tons) [48].

Cement type		Year							
		1990		2000		2010		2011	
		%		%		%		%	
Portland cement	Ordinary	62.2	76.3	49.4	69.5	27.7	67.1	27.8	69.3
	High early strength	3.5	4.3	3.2	4.6	2.1	5.2	2.2	5.3
	Others (A)	0.3	0.3	0.4	0.5	0.8	1.9	0.8	2.0
	Sub-total	66.0	80.9	53.0	74.6	30.6	74.2	31.7	76.6
Blended cement	Blast furnace slag	14.9	18.3	17.3	24.4	10.0	24.3	9.3	22.5
	Fly ash	0.5	0.7	0.7	1.0	0.2	0.4	0.1	0.2
	Others (B)	0.2	0.1	0.1	0.0	0.3	0.7	0.1	0.2
	Sub-total	15.6	19.1	18.1	25.4	10.5	25.4	9.5	22.9
Eco-cement						0.1	0.4	0.2	0.5
Total		81.6	100.0	71.1	100.0	41.2	100.0	41.4	100.0

Others (A): moderate heat cement, sulfate resisting cement, composite cement and low-heat cement.

Others (B): Pozzolan cement and composite cement.

Eco-cement: a completely new and revolutionary type of cement made primarily from the incinerator ash of municipal waste.

Table A2

Waste materials used in Japanese cement industry (unit: million tons) [48].

Item	Use	1990	1995	2000	2005	2010	2011
Blast furnace slag	RM	12.2	12.5	12.2	9.2	7.4	8.1
Coal ash	RM	2.0	3.1	5.1	7.2	6.6	6.7
Sewage, sludge	RM	0.3	0.9	1.9	2.5	2.6	2.7
By-product gypsum	RM	2.3	2.5	2.6	2.7	2.0	2.2
Waste soil	RM	–	–	–	2.1	1.9	1.9
Cinder, soot	RM, TE	0.5	0.5	0.7	1.2	1.3	1.4
Nonferrous slag	RM	1.2	1.4	1.5	1.3	0.7	0.7
Steel slag	RE	0.8	1.2	0.8	0.5	0.4	0.4
Wood chips	RM, TE	–	–	–	0.3	0.6	0.6
Waste plastic	TE	–	–	0.1	0.3	0.4	0.4
Others	RM, TE	2.5	3.0	2.5	2.3	2.1	2.0
Total	–	21.8	25.1	27.4	29.6	26.0	27.1
(kg/t-cement)		251	257	332	400	465	471

Waste soil: from construction.

Others: waste tire, degradation coal, reclaimed oil, waste oil, etc.

RM: raw material.

TE: thermal energy in cement kiln.

Japan Cement Association. (<http://www.jcassoc.or.jp/cement/2eng/eh3.html>).

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